



**Experiments on the Dominant Noise Sources in Centrifugal  
Turbomachinery Operating On and Off-Design**

**Final Technical Report**

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ONR Project Monitor:

Mr. James A. Fein

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**Final Technical Report**  
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**Turbomachinery Operating On and Off-Design**

SUMMARY OF RESEARCH 1992-94

ONR CONTRACT NO: N00014-93-1-0011

Program Manager: James A. Fein

**Technical Objectives**

The goal of this research was to develop an understanding of the strongest noise sources present in centrifugal turbomachinery with an aim of providing information toward the design of quieter machines. Previous investigations at Penn State revealed two noise production mechanisms. Additional research was initiated to enhance the understanding of the effect of geometric and flow modifications on noise production. Quantification of noise source types was also desired to determine the kind of interaction present at the impeller trailing edges. This, in turn, leads to information on methods to reduce noise.

More specifically, the objectives of the research were to assess the influence on the fluid dynamics and associated aeroacoustics of the centrifugal turbomachine of the following:

- 1) off-design operation
- 2) inlet flow distortion, and
- 3) trailing edge geometry.

## **Approach**

The overall approach to determine the relationship between the fluid dynamics and the radiated noise was consistent with past investigations by this group which involved careful measurements of both the acoustics and fluid dynamics of the impeller, discharge and where appropriate, the inlet flow field. The specific measurements involved hot-wire and pressure transducers mounted on the impeller, two microphones mounted in the volute free discharge and a pitot probe to survey the inlet mean flow (distortion).

## **Accomplishments of Last Year**

### **Off-design operation**

To more thoroughly investigate the aeroacoustics of our centrifugal turbomachine in off-design conditions, it was important to further enhance our experimental techniques to study the blade passage frequency and its harmonics as well as non-blade rate frequency components. Consequently, a major emphasis of the research group has been the development and implementation of data acquisition and reduction techniques designed to ascertain the types of noise sources previously identified with the centrifugal turbomachines. Initial investigations focused on the measurement and interpretation of ensemble averaged acoustic data to ascertain the directivity of the radiated noise.

In the first investigation measurements were conducted of the mean acoustic pressure radiated from the impeller as a function of the impeller position and frequency using an ensemble averaging technique. The results of these experiments can be interpreted as a measure of the impeller directivity. The technique was applied to two sets of experiments.

For the first set of experiments, the impeller directivities at the first and third harmonics of the blade passage tone were measured. Two microphones separated by 25.7 degrees were used for these experiments. By phase averaging, the microphone signals using the impeller encoder as a trigger, components at blade rate and its harmonics are enhanced. The phasing of various spectral components of the two microphone signals allows the rotating pressure pattern to be identified and quantified.

Next, measurements were conducted of the directivity of the interaction of the impeller trailing edges for the mode 14 component of the rotating instability. Several experiments were performed with different microphone spacings. The objective of these experiments was to identify and measure the acoustic field that is synchronized with the large scale instabilities that produce sound at other than blade passage frequency and its harmonics. Should this acoustic field be quantified, a great deal can be learned about the major noise generation processes. Further measurements are currently being conducted using more advanced acquisition and data reduction techniques.

#### Inlet flow distortion

Our studies of the effect of inlet flow distortion on the noise produced by the centrifugal impeller progressed very well. As expected, an inlet distortion significantly increased the noises produced at the blade passage frequency and its harmonics. We were uncertain as to what to expect for the broadband spectrum. The effect of significant inlet distortion on the broadband noise production was barely measurable.

## Trailing edge geometry

An ongoing series of experiments involve using the ensemble averaging technique to investigate the effect on the acoustic signal of systematically modifying the trailing edge flow of one or more impeller blades. Thus far, measurements are being conducted with the addition of a physical obstruction on the trailing edge of one blade and with a sharp edged extension on one blade. For each of these configurations, measurements are being conducted of the ensemble averaged acoustic signal, the blade trailing edge unsteady pressures, and the impeller discharge flow instability. The results are being assessed to evaluate the impact on noise production. By having the noise produced by one blade somewhat different than the other blades, we hope to measure the radiated sound and learn more of the noise production mechanisms.

## PAPERS:

- a. Total papers submitted to refereed journals:

Mongeau, L., D. E. Thompson, and D. K. McLaughlin, "**Method For Characterizing Aerodynamic Sound Sources in Turbomachines,**" Accepted for publication in *Journal of Sound and Vibration*, March 1993.

Dorney, D. J., Davis, R. L. and McLaughlin, D. K., "**Numerical Simulations of Flows in Centrifugal Turbomachinery.**" Submitted for publication to the *AIAA Journal*, August 1993.

Choi, J. S., D. K. McLaughlin, and D. E. Thompson, "**Measurements of Large Scale Instability Noise Generators in a Centrifugal Turbomachine.**" To be submitted for publication to *American Society of Mechanical Engineers, Journal of Turbomachinery*, November 1994.

Bent, P.H. and D.K. McLaughlin, "**Enhancements to Noise Source Measurement Techniques for Turbomachinery,**" to be submitted to the *Noise Control Engineering Journal*, November 1994.

b. Total number published in refereed journals:

Mongeau, L., D. E. Thompson, and D. K. McLaughlin, **"Sound Generation By Rotating Stall in Centrifugal Turbomachines,"** *Journal of Sound and Vibration*, Vol. 163, No. 1, 1993, pp. 1-30.

c. Total papers published in non-refereed journals:

Bent, P.H., McLaughlin, D.K., and Thompson, D.E., **"Influence of Flow Rate on Aerodynamic Noise Generation in Centrifugal Turbomachinery,"** Proceedings of the National Conference of Noise Control Engineering, Williamsburg, VA, May 2-5, 1993.

Dorney, D.J., Davis, R.L., and McLaughlin, D.K., **"Numerical Simulations of Flows in Centrifugal Turbomachinery,"** Paper no. AIAA 93-2578, AIAA/SAE/ASME/ASEE 29th Joint Propulsion Conference and Exhibit, Monterey, CA, June 28-30, 1993.

Tetu, L.G., D.E. Thompson, and D.K. McLaughlin, **"Aeroacoustic Similarity of Centrifugal Turbomachinery of Different Geometries,"** presented at the 15th AIAA Aeroacoustics Conference, AIAA Paper 4371, Long Beach, CA, October 25-27, 1993.

Bent, P.H., and D.K. McLaughlin, **"Enhancements to Noise Source Measurement Techniques for Turbomachinery,"** presented at the 15th AIAA Aeroacoustics Conference, AIAA Paper 93-4373, Long Beach, CA, October 25-27, 1993.

**NUMBER OF TECHNICAL REPORTS:** 6 (this past year)

**NUMBER OF BOOKS PUBLISHED:** 0

**NUMBER OF BOOK CHAPTERS PUBLISHED:** 0

**NUMBER OF PATENT APPLICATIONS:** 0

**SIGNIFICANT PRESENTATIONS:**

- a. Total number: 5
- b. List of top 3:

Bent, P.H., McLaughlin, D.K., and D.E. Thompson, **"Influence of Flow Rate on Aerodynamic Noise Generation in Centrifugal Turbomachinery,"** Presented at the National Conference of Noise Control Engineering, Williamsburg, VA, May 2-5, 1993.

Dorney, D.J., Davis, R.L., and McLaughlin, D.K., **"Numerical Simulations of Flows in Centrifugal Turbomachinery,"** Paper no. AIAA 93-2578, AIAA/SAE/ASME/ASEE 29th Joint Propulsion Conference and Exhibit, Monterey, CA, June 28-30, 1993.

Bent, P.H., and D.K. McLaughlin, "Enhancements to Noise Source Measurement Techniques for Turbomachinery," Presented at the 15th AIAA Aeroacoustics Conference, AIAA Paper 93-4373, Long Beach, CA, October 25-27, 1993.

#### HONORS AND AWARDS RECEIVED BY PI'S:

AIAA Air Breathing Propulsion Technical Committee Best Paper for 1993 for, "Numerical Simulations of Flows in Centrifugal Turbomachinery," by D.J. Dorney, R.L. Davis, and D.K. McLaughlin.

NUMBER OF DIFFERENT POST DOCS SUPPORTED/PERSON-MONTHS: 0

NUMBER OF DIFFERENT GRADUATE STUDENTS SUPPORTED/PERSON-MONTHS:

Paul H. Bent	48	PhD Received:	Dec. 1992
Lee G. Tetu	32	MS Received:	Aug. 1993, PhD Candidate
Matt Hettenhouse	12	MEng Received:	Aug. 1994

#### MOST SIGNIFICANT PUBLICATIONS (including short abstract):

Mongeau, L., D. E. Thompson, and D. K. McLaughlin, "Sound Generation By Rotating Stall in Centrifugal Turbomachines," *Journal of Sound and Vibration*, Vol. 160, No. 4, 1993.

#### Abstract

Experiments were conducted in order to investigate the relatively low frequency aerodynamic sound generating mechanisms in centrifugal turbomachines. A facility consisting of a centrifugal water pump impeller with various discharge configurations and an inlet duct was designed and built for the experiments. Air was used as the fluid medium. The inlet duct provided a controlled, quiet inflow to the impeller. Measurements of the acoustic noise radiated in the pump surroundings were made in parallel with fluid dynamic measurements in order to establish correlations. The most significant conclusion reached is that a form of rotating stall dominated the low frequency noise production in various configurations with no outlet diffuser or casing.

Measurements of the inlet-radiated noise were made over a wide range of pump operating conditions; a method of scaling the data, based on similarity laws, was used as a means of separating source characteristics from the acoustic loading. Source spectra with no diffuser showed strong peaks centered at about 0.7, 1.4, 2.1 ... times blade passing frequency. Aerodynamic pressure spectra measured at a single point on a rotating impeller blade were found to contain a cluster of harmonically related narrow-

band tones, based on a fundamental around 0.7 times the shaft rotation frequency. Every seventh tone (harmonics 7, 14, 21 ...) was strongly coherent with the acoustic signal. Measurements of unsteady discharge velocity were made with two stationary hot-wire probes at varying azimuthal separations close to the impeller exit. Spatial and temporal analysis revealed an almost-frozen multi-lobed pattern rotating at around 30% shaft speed. The following hypothesis is put forward on the evidence of the measurements: the prominent peaks in the acoustic signature of the diffuserless impeller represent rotating stall noise, generated by aerodynamic interaction between the rotating stall pattern and the impeller blades.

Choi, J. S., D. K. McLaughlin, and D. E. Thompson, "**Measurements of Large Scale Instability Noise Generators in a Centrifugal Turbomachine.**" To be submitted for publication to *American Society of Mechanical Engineers, Journal of Turbomachinery*, 1994.

#### Abstract

The objective of this research was to measure the mean flowfield and the large scale instability noise generators in a centrifugal turbomachine. Measurements have been made with hot-wire sensors mounted on the impeller and in the discharge flow of an impeller operating without a cut-off and volute. The velocities at the discharge show a jet-wake type of flow pattern which results in a strong vorticity field. The flow with high velocity found on the pressure side tends to move to the low pressure region present at the suction side of a impeller as a form of roll-up around the blade trailing edge. This flow motion is believed to cause a unsteady flow separation at the suction side of the blade and consequently to disturb the flow in the adjacent passage. The unsteadiness is unusually coherent over the whole impeller discharge. The experiments show how the large scale instability, rotating at a small fraction of the shaft speed, interacts with the trailing edges of the impeller blades to produce a dominant portion of the resulting noise. The resulting radiated noise spectra are shown to be dominated by harmonically related broad humps at approximately 70%, 140%, and 210% of the blade passage frequency.

Mongeau, L., D. E. Thompson, and D. K. McLaughlin, "**Method For Characterizing Aerodynamic Sound Sources in Turbomachines,**" Accepted for publication in *Journal of Sound and Vibration*, March 1993.

#### Abstract

A method based on Weidemann's acoustic similarity laws [1] was used to investigate the aerodynamic sound generated by a partially ducted centrifugal pump rotor. The objective of the method was to determine the spectral characteristics of the sound source by isolating the effects of acoustic phenomena such as duct resonances or sound reflections.

Pump-radiated sound pressure spectra were measured for different impeller rotational speeds, keeping the operating condition constant. The spectra, assumed to be expressed as the product of a source spectral distribution function and an acoustic frequency response function, were then decomposed into a product form following a computer-implemented algorithm.

Bent, P.H. and D.K. McLaughlin, "Enhancements to Noise Source Measurement Techniques for Turbomachinery," to be submitted to the *Noise Control Engineering Journal*, 1994.

### Abstract

The experimental identification and interpretation of aeroacoustic sources in turbomachinery can be simplified if the effects of propagation are removed from the measured data to reveal the spectrum of the acoustic source alone. This paper describes two enhancements to an existing technique for extracting the acoustic source spectrum from measurements contaminated by the acoustic response of the surroundings. These enhancements allow the true level of the acoustic source and the dependence of the noise generation process on impeller tip Mach number to be established. To illustrate these enhancements they are applied to the analysis of noise generated by a centrifugal pump impeller. As part of the development of the enhancements presented here, a deeper theoretical insight into the process of spectral decomposition is attained.

The source spectral distribution function was found to be independent, within an arbitrary constant value, of the microphone location and the acoustic loading. Therefore, the method was successful in accurately determining the spectral characteristics of the broadband aerodynamic noise generating mechanisms involved.

### ACCOMPLISHMENTS:

The research group had made specific advances in three major areas:

- 1) Detailed time-mean and unsteady aerodynamic measurements have been made which have identified and quantified a large scale stall-like instability in the centrifugal impeller flowfield, and determined properties of the turbulent boundary layers that produce the broad-band noise. A focus of the past year has been to establish these properties in off-design operating conditions.
- 2) The effect of significant inflow distortion on the noise produced by our centrifugal impeller was quantified.

- 3) Experiments investigating the effect of detailed design of impeller blade trailing edges have demonstrated that this avenue of investigation promises to provide two benefits. First some information on trailing edge geometries that reduce noise production is obtained. Second, by making modifications to only one blade, and processing the radiated noise signals measured at two positions, valuable information on the noise generation mechanisms is determined. This research is a focus of the ongoing research in centrifugal turbomachinery noise in our laboratory.

### **SIGNIFICANT TRANSITIONS:**

The method of separating a source signal from a signal which contains both the source signal and transmission effects has been used in several Navy research programs at ARL Penn State. The particular application adapts the method developed by Mongeau ("Method for Characterizing Aerodynamic Sound Sources in Turbomachines") to a propeller shaft upon which the propeller unsteady forces are being measured. These unsteady force measurements are contaminated by shaft vibration. The method removes the vibration effects and produces the desired unsteady forces. This method has been used for both model and full-scale measurements.

Additionally the method described above has also been adopted by the following organizations: 1) United Technologies Research Center (R.H. Schlinker), 2) AT&T Bell Labs, computer cooling fan quieting, (P.H. Bent), and 3) Purdue University Herrick Laboratories (L. Mongeau), 4) Ingersoll-Rand, pump quieting work, 5) Allison Engine Company, turbine engine quieting (P. Tramm), 6) CDNSWC - ANN, pump quieting.

### **IMPACT OF THE RESEARCH:**

The research has laid a foundation of understanding of two of the basic fluid dynamic processes in the production of broadband noise in centrifugal turbomachinery. This basic understanding is now available to development engineers who are working on future designs that will operate with significantly reduced noise emission.